

Does PIONEER measure local spacetime expansion?

Hans-Jörg Fahr and Mark Siewert

Argelander-Institut f. Astronomie, Abt. Astrophysik
hfahr@astro.uni-bonn.de msiewert@astro.uni-bonn.de

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Abstract

There is a longstanding mystery connected with the radiotracking of distant interplanetary spaceprobes like ULYSSES, Galileo and especially the two NASA probes PIONEER 10 and 11. Comparing radiosignals outgoing from the earth to the probe and ingoing again from the probes do show anomalous frequency shifts which up to now have been explained as caused by anomalous non-Newtonian decelerations of these probes recognizable at solar distances beyond 5 AU. In this paper we study cosmological conditions for the transfer of radiosignals between the Earth and these distant probes. Applying general relativity, we derive both the geodetic deceleration as well as the cosmological redshift and compare the resulting frequency shift with the observed effect. We find that anomalous decelerations do act on these probes which are of cosmological nature, but these are, as expected from standard cosmology, much too low to explain the observed effect. In contrast, the cosmological redshift of radiophotons suffered during the itinerary to the probe and back due to the local spacetime expansion reveals a frequency shift which by its magnitude is in surprisingly good agreement with the long registered phenomenon, and thus explains the phenomenon well, except for the sign of the effect. Problems of a local Hubble expansion may give the reason for this.

1 Introduction to the PIONEER phenomenon

Besides other fundamental problems in present astrophysics and cosmology, for instance connected with the nature of black holes, Quasars, Gamma ray bursters, dark matter or dark energy, there exists since about 20 years now the well recognized fundamental problem connected with an anomalous deceleration towards the Sun registered at the motion of the deep space probes like PIONEER-10 and 11 (see Anderson et al. 1998). Meanwhile these anomalous decelerations have also been recognized at the spaceprobes Galileo and Ulysses (Anderson et al. 2002b). Nevertheless the PIONEER spacecraft are especially

appropriate for dynamical astronomy studies due to the very accurate radio-tracking operating for them. Due to their spin-stabilization their acceleration estimates come down to the level of $10^{-10} cm/s^2$. The VOYAGER spacecraft in this respect are much less suited for precise celestial mechanics experiments as they perform too many attitude control maneuvers overwhelming all small external accelerations.

Since 1980, when PIONEER-10 moved at solar distances larger than 20 AU and the Newtonian solar gravity pull dropped to levels of $\alpha_s \leq 5 \cdot 10^{-8} cm/s^2$, the JPL orbit determination program (ODP) found unmodelled accelerations with a systematic residual level of $\alpha_a \simeq (8.74 \pm 1.33) \cdot 10^{-8} cm/s^2$ directed towards the sun. Interestingly enough the level of these residual decelerations, besides some 10 percent fluctuations, remained constant for all the ongoing PIONEER itinerary to larger distances, i.e. seemed to prove as being independent on solar distance, orientation and time. A large number of proposals how these anomalous decelerations could perhaps be explained have meanwhile been proposed (see Anderson et al. (2002b) or Dittus and Lämmerzahl (2006)). Amongst them one finds friction forces with interplanetary dust grains, asymmetric thermal emission from the probe, an accelerated motion of the whole solar system in the direction normal to the ecliptic, MOND effects or dark matter gravity contributions have been discussed, but none of these proposed explanations up to now could fit the observed magnitude and the distance-independence of the anomalous deceleration. For this reason more recently also cosmological causes for the existing anomalous deceleration have been suspected, all the more because the value found for the anomalous deceleration nicely is represented by the cosmological quantity $\alpha_a \simeq cH_0$, where H_0 denotes the present-day Hubble constant of about the order of 70 km/s/Mpc.

2 The local equation of geodetic motion

Spoken in terms of general relativity, the solar system is embedded into a local spacetime metric which is not of purely cosmological nature, but locally has an imprint from gravitational binding forces of gravitationally bound masses of our host galaxy, i.e. the milky way. It should be noted that there is some doubt that local cosmological expansion does even exist below the scale of galaxy clusters (Misner et al. 1973). However, there are results by other authors who believe differently (see Bonnor 2000, and references therein, for a recent review), and the final answer to this question is still to be given. For this reason we now try to estimate what kind of forces (and other effects) would result from such a contribution.

The first attempt to describe gravitationally bound masses embedded in the Robertson-Walker metric of an expanding universe goes back to Einstein and Straus (1945). As shown there the connection of an outer Schwarzschild metric of a central mass M to an outer cosmic Robertson-Walker metric seems possible at a critical distance r_{ES} from the central mass, which is called the Einstein-Straus

vacuole. This critical radius is given by:

$$r_{ES} = \left(\frac{3M}{4\pi\rho_0} \right)^{1/3}. \quad (1)$$

It turns out that, since in an expanding universe, the mass density ρ_0 is decreasing with time, the radius of the ES-vacuole increases with time according to

$$\frac{\dot{r}_{ES}}{r_{ES}} = \frac{\dot{R}}{R} = H_0. \quad (2)$$

The main problem connected to the ES-vacuole is that, in the present time, it is very large, i.e. $r_{ES}(1M_\odot) \simeq 100pc$ and $r_{ES}(1M_{Gal} = 10^{11}M_\odot) \simeq 0.5Mpc$. This means that, if ES-vacuoles would really surround bound systems, such as galaxies, then essential fractions of cosmic space would be described by the static Schwarzschild metric within these vacuoles instead of the Robertson-walker one. This relation has also been pointed out by Carrera and Giulini (2006). For the well-established cosmological photon redshift, this means that this quantity would be no longer related to the cosmological distance, invalidating one of the most fundamental results from cosmology.

The problem of the actually prevailing cosmic metrics within gravitationally bound systems is still highly controversial at present, as demonstrated in a recent paper by Carrera and Giulini (2006). These authors also demonstrate, using clear astrophysical arguments, that the answer given by Einstein and Straus (1945) and successor papers is not able to adequately solve this problem. They argue in their paper that in an expanding Robertson-Walker universe, to keep a test mass m at a timelike distance r from the center of the solar gravity, a cosmological acceleration has to operate which is given by:

$$|\ddot{r}|_{CA} = \left(\frac{\ddot{R}_0}{R_0} \right) r = -q_0 H_0^2 r, \quad (3)$$

where R_0 , q_0 and H_0 denote the present scale of the universe, the acceleration parameter and the Hubble constant. The classical Newtonian gravity force hence only includes the residual acceleration and leads to the following equations of motion:

$$m(\ddot{r} - |\ddot{r}|_{CA}) = -\frac{C}{r^2} + \frac{L^2}{r^3} \quad (4)$$

and:

$$L = r^2 \dot{\phi} \quad (5)$$

where C contains the central mass of the sun, L is the angular momentum of the orbiting object, and the azimuth has been denoted with ϕ . These modified equations can also be applied to an object like the PIONEER spacecraft, but it clearly turns out that the cosmological acceleration is unable to explain the anomalous frequency shifts of the PIONEER signals.

We consider the PIONEER spacecraft as an object carrying out only a geodesic motion in the local spacetime metrics of the surrounding universe, with a

time-dependent Robertson-Walker-like metric with a local scale parameter L (LRW-metric) and the associated Christoffel symbols, which in turn are a function of first partial derivatives of the metrical tensor g_{ik} ,

$$\Gamma_{jk}^i = \frac{1}{2}g^{il}(\partial_j g_{lk} + \partial_k g_{lj} - \partial_l g_{jk}). \quad (6)$$

The general-relativistic generalisation of the simple Newtonian force-law then is

$$\frac{d^2 x_\alpha}{ds^2} + \Gamma_{\mu\nu}^\alpha \frac{dx_\mu}{ds} \frac{dx_\nu}{ds} = f^\alpha, \quad (7)$$

with the spacetime coordinates $x_\alpha = \{x_0, x_1, x_2, x_3\} = \{ct, r, \vartheta, \phi\}$ and the world line element $ds = c \, d\tau = c\gamma(v)dt$. The expression f^α is the four-force/mass, representing the gravitational pull of the sun, and other external forces, while $\gamma(v) = (\sqrt{1 - v^2/c^2})^{-1}$ is the well known relativistic Lorentz factor. The coordinate system has been selected in a way that the center ($r = 0$) is located in the sun (i. e. approximately at the earth).

Assuming now that the four-force/mass does systematically vanish at larger distances from the sun, one is left with the geodetic equation for freely moving particles

$$\frac{d^2 x_\alpha}{ds^2} + \Gamma_{\mu\nu}^\alpha \frac{dx_\mu}{ds} \frac{dx_\nu}{ds} = 0. \quad (8)$$

For a purely radial motion, i.e. an object only changing the increment of r at its motion, with $d\vartheta, d\phi = 0$, eqn. 8 reduces to

$$\begin{aligned} & \frac{d^2 r}{ds^2} + \Gamma_{\mu\nu}^r \frac{dx_\mu}{ds} \frac{dx_\nu}{ds} \\ &= \frac{d^2 r}{ds^2} + \left\{ \Gamma_{0\nu}^r \frac{dx_0}{ds} + \Gamma_{r\nu}^r \frac{dr}{ds} \right\} \frac{dx_\nu}{ds} \\ &+ \left\{ \Gamma_{\nu 0}^r \frac{dx_0}{ds} + \Gamma_{\nu r}^r \frac{dr}{ds} \right\} \frac{dx_\nu}{ds} \\ &= 0. \end{aligned} \quad (9)$$

After a quick sorting this expression further reduces to

$$\begin{aligned} \frac{d^2 r}{ds^2} = -2 \left\{ \Gamma_{00}^r \left(\frac{dx_0}{ds} \right)^2 + \Gamma_{r0}^r \frac{dr}{ds} \frac{dx_0}{ds} \right. \\ \left. + \Gamma_{0r}^r \frac{dr}{ds} \frac{dx_0}{ds} + \Gamma_{rr}^r \left(\frac{dr}{ds} \right)^2 \right\}. \end{aligned} \quad (10)$$

We now consider a local Robertson-Walker-type metric (LRW metric), for which the coefficients are given by

$$\begin{aligned} g_{tt} &= 1 & g_{rr} &= -\frac{L^2(t)}{1 - kr^2} \\ g_{\vartheta\vartheta} &= -L^2(t)r^2 & g_{\phi\phi} &= -L^2(t)r^2 \sin^2 \vartheta \end{aligned} \quad (11)$$

$$\begin{aligned}\Gamma_{rr}^r &= \frac{rk}{1 - kr^2} & \Gamma_{00}^r &= 0 \\ \Gamma_{0r}^r &= \frac{1}{c} \frac{\dot{L}}{L} & \Gamma_{r0}^r &= 0,\end{aligned}\tag{12}$$

where k is the curvature parameter and $L(t)$ is the local scale factor.

Thus one finally obtains the following differential equation in coordinates r and s

$$\frac{d^2 r}{ds^2} = -\frac{2}{c} \frac{\dot{L}}{L} \frac{dr}{ds} - \frac{2rk}{1 - kr^2} \left(\frac{dr}{ds}\right)^2.\tag{13}$$

For subrelativistic object velocities, i.e. $\gamma(v) = 1$, this expression transforms into

$$\frac{d^2 r}{dt^2} = -\frac{2\dot{L}}{L} \frac{dr}{dt} - \frac{2rk}{1 - kr^2} \left(\frac{dr}{dt}\right)^2.\tag{14}$$

Assuming that the universe is flat ($k = 0$), this expression further reduces to

$$\frac{d^2 r}{dt^2} = -\frac{2\dot{L}}{L} \frac{dr}{dt}.\tag{15}$$

For a purely radial motion, the metric line element is given by the expression

$$ds_r = \sqrt{-g_{rr}} dr = L \frac{dr}{\sqrt{1 - kr^2}}.\tag{16}$$

Using again $k = 0$, this relation simplifies to

$$s_r = Lr,\tag{17}$$

and the radial velocity becomes

$$v_r = \frac{ds_r}{dt} = \dot{L}r + L \frac{dr}{dt},\tag{18}$$

which can be rearranged to

$$\frac{dr}{dt} = \frac{1}{L}(v_r - \dot{L}r).\tag{19}$$

Differentiating eqn. 18 leads to an equation for the radial acceleration b_r ,

$$b_r = \frac{d^2 s_r}{dt^2} = \ddot{L}r + 2\dot{L} \frac{dr}{dt} + L \frac{d^2 r}{dt^2}.\tag{20}$$

Applying eqns. 15 and 19, it is possible to eliminate all nonmetric quantities by metric ones and the differential equation 20 turns into the metrical equation

$$b_r = s_r \frac{\ddot{L}}{L}.\tag{21}$$

This expression is nonzero if we assume that the universe is not only expanding, but accelerating, which has been verified by recent observations of distant

supernovae Perlmutter et al. (1999) as well as CMB radiation by the WMAP experiment (WMAP). On the other hand, this expression depends on the distance of the spacecraft from the sun, which contradicts the distance-independence of the observed PIONEER effect (see Anderson et al. 2002b).

If we assume that cosmological expansion is an upper limit to what may happen on smaller scales, i. e. $\ddot{L} = \ddot{R}$, then, using

$$q_0 = -\frac{\ddot{R}R}{\dot{R}^2} \simeq \frac{1}{2}, \quad (22)$$

we obtain

$$b_r < -s_r q_0 H_0^2. \quad (23)$$

Interestingly, this result is almost identical to the result from Carrera and Giulini (2006), where the relation $\ddot{a}/a \simeq -q_0 H_0^2$ was found. From these two equations it follows that, in order to reproduce $b_r \simeq H_0 c$, and using typical values of $s_r = o(10AU)$ and $q_0 = o(1)$, we need

$$s_r = o(10^{26})m \simeq o(10^{15})AU. \quad (24)$$

Thus, at the distances covered by the PIONEER spacecrafts, the resulting force is much too weak to be observable.

To summarize our results, if cosmological expansion is present on the length scale of the solar system, its effect in terms of anomalous acceleration would definitely not be able to explain the observed blueshift in the PIONEER signal.

3 The cosmological redshift of radiophotons

Another, considerably different possibility to explain the anomalous PIONEER acceleration, is to assume that the observed effect is a “fake” acceleration, which in truth follows from some fundamental misunderstanding about the underlying physics of radiowave propagation in space. While a considerable amount of work has been put into tracking down additional gravitational sources, there have only been a few publications investigating this other possibility in the past years. Rosales and Sanchez-Gomez (1999) and Rosales (2002) have investigated the possibility of a systematical error in the measurement of cosmological distances and times, obtaining a result with the correct order of magnitude. However, Carrera and Giulini (2006) claim that this estimate is wrong, and that the result should be reduced by an order of $(v/c)^3$.

We now investigate a different possibility related to cosmological expansion, namely the redshift suffered by massless particles (such as radiophotons) freely propagating through an expanding space. According to JPL (ODP), the registered phenomenon of the PIONEER anomaly by formula is represented in the form (Anderson et al. 2002b)

$$\Delta\nu = \nu_0 - \nu_1 = -\nu_0 \frac{2a_{PIO}t_i}{c}, \quad (25)$$

where the time is normalized in a way that $2t_i$ denotes the passage time of the electromagnetic radio signal on its way from the Earth to the spaceprobe and back to the receiver on earth, and a_{PIO} denotes the expected so-claimed residual acceleration in the PIONEER motion, normalized in a way that $a_{PIO} > 0$ corresponds to an acceleration towards the sun. The subscript 1 denotes the quantities at $t = 2t_i$, when the returning photon is observed. It should be noted that the above frequency shift is normalised in a different way than usual, where a redshift results in $\Delta\nu > 0$ and a blueshift in $\Delta\nu < 0$ (see Anderson et al. 2002b, ref. 38, the "usual" definition results in an additional negative sign).

The cosmological wavelength-redshift relation for a photon in a local Robertson-Walker-like spacetime (LRW-metric) is

$$\frac{\lambda_1}{\lambda_0} = \frac{\nu_0}{\nu_1} = \frac{L_1}{L_0}, \quad (26)$$

where the subscript 0 denotes the respective value of the emitted photon, while the subscript 1 denotes the observed, redshifted photon. Here we have called the initial scale factor $L(t=0) = L_0$ and the scale factor at $t = 2t_i$ is called L_1 . For this scale factor and for short distances it is possible to expand $L_1 = L_0 + \dot{L}_0 \cdot 2t_i$ and we obtain

$$\Delta\nu = \nu_0 - \nu_1 = \nu_0 \left(1 - \frac{L_0}{L_1} \right) = \nu_0 \left(1 - \frac{L_0}{L_0 + \dot{L}_0 2t_i} \right). \quad (27)$$

Assuming that $(\dot{L}/L) \cdot 2t_i \ll 1$, this expression further simplifies to

$$\Delta\nu = \nu_0 \left(1 - \frac{1}{1 + \frac{\dot{L}_0}{L_0} 2t_i} \right) \simeq \nu_0 \left(1 - 1 + \frac{\dot{L}_0}{L_0} 2t_i \right). \quad (28)$$

If we compare this expression with eqn. 25, we obtain

$$\Delta\nu = -\nu_0 \frac{a_{PIO} t_i}{c} = \nu_0 \frac{\dot{L}_0}{L_0} t_i, \quad (29)$$

and finally

$$a_{PIO} = -\frac{\dot{L}}{L} c. \quad (30)$$

For a full cosmological expansion, we obtain

$$a_{PIO} = -H_0 c. \quad (31)$$

Except for the sign, this result is in remarkably good agreement with the observed anomalous acceleration term, $a_{PIO} \simeq H_0 c$.

Ignoring the wrong sign, we obtain numerically for $a_{PIO} = (8.74 \pm 1.33) \cdot 10^{-10} m/sec^2$

$$\begin{aligned} H_0 &= |a_{PIO}| = (2.91 \pm 0.44) \cdot 10^{-18} s \\ &= (89.8 \pm 13.5) \frac{km}{s \text{ Mpc}}, \end{aligned} \quad (32)$$

which is only marginally different from the observed value of the Hubble constant, namely $H_0 = (70 + 2.4 - 3.2) km/(sMpc)$.

4 The local spacetime expansion

We consider the metric conditions of the space environment of our solar system and of the milky way as it may be described by a local metrical perturbation of the general cosmological spacetime metrics (i.e. the RW-metrics) due to the enhanced matter density in the local cosmic environment compared to the large-scale average of cosmic matter density. Bonnor (1957) has described this situation by introduction of a function called the local density contrast δ and given by:

$$\delta(L, t) = \frac{\rho(L, t) - \langle \rho(t) \rangle}{\langle \rho(t) \rangle} = \frac{\Delta \rho(L, t)}{\langle \rho(t) \rangle}, \quad (33)$$

where $\rho(L, t)$ and $\langle \rho(t) \rangle$ denote the average density over a scale L and the large-scale average (i. e. $L \rightarrow L_\infty \simeq \infty$) of the cosmic matter density, respectively. For the growth of this function Bonnor has derived the following differential equation:

$$\ddot{\delta} + 2\frac{\dot{R}}{R}\dot{\delta} - 4\pi G \langle \rho(t) \rangle \delta = 0. \quad (34)$$

The solution of this differential equation for an Einstein-DeSitter type universe with $\Lambda = 0$ and $k = 0$ is given by (see, e. g. Goenner (1997) or Silk and Bouwens (2001))

$$\delta = \delta_0 \left(\frac{t}{t_0} \right)^{2/3}, \quad (35)$$

where δ_0 is the density contrast at some reference time t_0 .

Considering galaxies with a typical scale L and typical mass M_{gal} one can express the density contrast on the galactic scale by:

$$\delta(L(t)) = \frac{\frac{M_{gal}}{L^3}}{\frac{M_U}{R^3}} - 1 = \left(\frac{M_{gal}}{M_U} \right) \left(\frac{R}{L} \right)^3 - 1, \quad (36)$$

with the expression

$$\langle \rho(t) \rangle = M_U / R(t)^3. \quad (37)$$

From that relation we derive

$$\left(\frac{M_{gal}}{M_U} \right) \left(\frac{R}{L} \right)^3 - 1 = \delta_0 \left(\frac{t}{t_0} \right)^{2/3}. \quad (38)$$

Since the present day density contrast has grown to very large values of the order of $\delta \simeq 10^6$ we thus can find:

$$L = R \left(\frac{M_{gal}}{M_U} \right)^{1/3} \delta_0^{-1/3} \left(\frac{t_0}{t} \right)^{2/9} = R \Gamma \left(\frac{t_0}{t} \right)^{2/9}, \quad (39)$$

with $\Gamma = \left(\frac{M_{gal}}{M_U} \right)^{1/3} \delta_0^{-1/3}$. By differentiating eqn. 39 we obtain

$$\dot{L} = \dot{R} - \frac{2}{9} \frac{L}{t}, \quad (40)$$

or

$$\frac{\dot{L}}{L} = H_0 \left(1 - \frac{2 T_0}{9 t} \right), \quad (41)$$

where T_0 is the Hubble age of the universe and t the time since which the initial density contrast has been evolving, say, the matter recombination era when δ_0 was of the order of $\delta_0 \simeq 10^{-5}$ (see WMAP). For a linearly expanding universe we then get $t \simeq T_0$ and

$$\frac{\dot{L}}{L} = H_0 \left(1 - \frac{2}{9} \right) = \frac{7}{9} H_0. \quad (42)$$

Applying this expression to eqn. 30 leads to

$$a_{PIO} = -\frac{7}{9} H_0 c. \quad (43)$$

This means that the predicted redshift is no longer as red as expected on a cosmological length scale, but it still spots the wrong sign.

Can we use this mechanism to obtain the observed blueshift? This would require

$$\frac{7 T_0}{9 T_r} - 1 \simeq 1, \quad (44)$$

which in turn leads to a required true recombination age of the universe (T_r) of

$$T_r \simeq \frac{7}{18} T_0, \quad (45)$$

which isn't even half the (Hubble) age of the universe.

Comparing this with the current experimental result that the universe seems to be uncurved ($k = 0$), and undergoing an accelerating expansion, the only RW-like cosmological model which qualitatively fits these observations is the variant using $\Lambda > 0$, which predicts an *older* Universe than inferred from the Hubble constant (see, e.g. d'Inverno 1998). From this we conclude that even after correcting our results from the last section for local perturbations by the galaxy in a (linear) Einstein-DeSitter type universe our ansatz still can't explain the PIONEER anomaly.

On the other hand, the above derivation is based on the theory of linear growth of density contrasts. Starting, however, from initial levels of the order of $\delta_0 \simeq 10^{-5}$ at the recombination era, density contrasts meanwhile have grown up to to strongly nonlinear levels of the order of $\delta \simeq 10^6$ in the present universe. Thus linear perturbation theories as they were applied in the derivations above lead to misleading results. In case of strongly nonlinear growth the local scale L may, in fact, even still now undergo a local cosmological blueshift instead of the redshift of freely propagating photons in the milky way environment. Since analytical results on the nonlinear growth of density contrasts do not exist yet, we instead try an alternative way to describe the rate of a local cosmological expansion. At the recombination era, with a cosmological redshift of $z_r = 1000$,

the cosmic density was given by $\rho_r = 10^9 \rho_0$, where ρ_0 denotes the present-day cosmic density. On the other hand, the present-day density contrast on the galactic scale is given by

$$\delta_0(L_{gal}) = \frac{\rho_{gal} - \rho_0}{\rho_0} \simeq 10^6. \quad (46)$$

This indicates that the mass density on the galactic scale has only decreased by three orders of magnitude since the recombination era, clearly pointing to the fact that the cosmic volume forming a present-day galaxy has expanded differentially with respect to the rest of the universe, roughly given by the expansion law

$$L_{gal,0} = L_{gal,r} \left(\frac{R_0}{R_r} \right)^\alpha, \quad (47)$$

with $\alpha \simeq 1/2$. From this relation it is possible to derive the expansion law

$$\frac{\dot{L}_{gal,0}}{L_{gal,0}} = \frac{1}{2} \frac{\dot{R}_0}{R_0}. \quad (48)$$

On the basis of this relation we estimate the resulting frequency shift by

$$\delta\nu = \frac{\nu_0}{2} H_0 t, \quad (49)$$

which corresponds to a fake acceleration of

$$a_{PIO} = -\frac{H_0 c}{2}. \quad (50)$$

This result, however, is still a redshift, instead of the observed blueshift.

5 Conclusions and outlook

In this paper we have investigated several ideas on how it might be possible to explain the much discussed PIONEER anomaly, which consists of an unexplained blueshift of radiophotons compared to the predicted values. This effect, which is usually interpreted in terms of an unexplained acceleration towards the sun (Anderson et al. 1998, 2002b), can not be explained as due to cosmological acceleration effects. Although the geodetic motion of an object, like PIONEER-10, in an expanding universe does lead to residual accelerations in a flat Robertson-Walker-like universe, these accelerations are off by many orders of magnitude, and they are also incompatible with the seemingly constant effect which makes up the anomaly.

We have also demonstrated that, except for a wrong sign, the order of magnitude of the observed frequency shift is of the same order as the global cosmological redshift which occurs when photons propagate freely in the local spacetime. This redshift has been successfully applied by countless astronomers to explain

the observed redshift from distant quasar and galaxy emission lines. The interesting similarity between the numerical results may also hint at a systematical error in the physics applied to the analysis of the data.

Since the PIONEER spacecraft is propagating in a local density fluctuation (the milky way), we have also estimated the corresponding imprint of the local gravitationally bound system in a universe with linear expansion. It has been demonstrated that, although spacetime probably is not expanding in a linear way (assuming that it is expanding on a local length scale at all), this effect is, in principle, able to correct the wrong sign in the local redshift. For these reasons, more research on this field is strongly encouraged.

Confirming a cosmologically-induced frequency shift with PIONEER or any upcoming, similarly appropriate, future spacecraft missions (see, e.g. Anderson et al. 2002a) would help clarify this extremely important problem of the nature of local spacetime metrics and therefore help to predict a still ongoing density contrast enhancement on the universe for time periods in the near future.

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